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The Impact of Active Aeroelastic Wing Technology on Conceptual Aircraft Design

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Abstract

Active Aeroelastic Wing (AAW) Technology represents a new design approach for aircraft wing structures. The technology uses static aeroelastic deformations as a net benefit during maneuvering. AAW is currently being matured through a flight research program[1]; however, transition of the technology to future systems will require educating designers in multiple disciplines of this new design approach. In order to realize the full benefits of AAW, aeroelastic effects will need to be accounted for from the beginning of the design process. Conceptual design decisions regarding parameters such as wing aspect ratio, wing thickness-to-chord ratio (t/c), and wing torque box geometry may be influenced, if designers choose to utilize AAW.

This paper presents recent efforts in developing conceptual aircraft design guidance for AAW technology and identifies improvements to the design process that could facilitate future AAW design applications. This process involves using results from aeroelastic design methods, typically used in preliminary design, with conventional conceptual design methods. This approach will allow aeroelastic effects to be considered in making conceptual design decisions.

Introduction

Conventional aircraft design philosophy views the aeroelastic deformation of an aircraft wing as having a negative impact on aerodynamic and control performance. The twisting of a wing due to aileron deflection during a roll maneuver can produce the phenomena of aileron reversal. Aileron reversal is the point where the deflection of the aileron produces no rolling moment. That is, the rolling moment produced by the change in camber due to aileron deflection is offset by the effective reduction in wing angle of attack due to the aeroelastic wing twist. Aircraft designers have generally tried to limit the effects of aeroelastic deformation by designing geometrically stiff planforms (low aspect ratio, high t/c), increasing structural weight to provide additional stiffness, and/or using horizontal tails to provide supplemental roll moment. A conventional wing design presents a severe compromise between aerodynamic, control, and structural performance.

Active Aeroelastic Wing (AAW) technology is a new wing structural design approach that integrates flight control design to enhance aerodynamic, control, and structural performance.[2] AAW exploits inherent structural flexibility as a control advantage, utilizing both leading and trailing edge control surfaces to aeroelastically shape the wing. The entire wing acts as a control surface, with the leading and trailing edge surfaces acting as tabs. The power of the air stream is used to twist the wing into a favorable shape. The degree of deformation is not necessarily any more than for a conventional wing; however, the deformation is advantageous instead of adverse to the maneuver (See Figure 1). AAW can be used to generate large roll control authority at higher dynamic pressures, and enables maneuver load control for both symmetric and asymmetric maneuvers. AAW does not require "smart structures", advanced actuation concepts, or adaptive control law techniques; however, AAW may complement these other advanced technologies. The key difference between AAW and the conventional approach is the exploitation of aeroelastic methods throughout the design process.

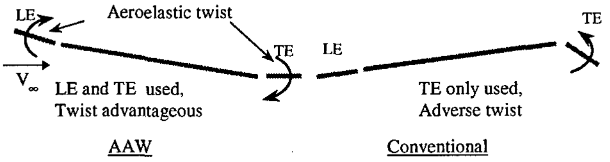

Figure 1. AAW vs. Conventional Roll Maneuver

The AAW approach removes static aeroelastic constraints in the wing design. Previous studies have

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shown that an AAW can generate sufficient roll moment without the need for a horizontal tail to provide supplemental roll moment.[2,3,4] AAW expands the design space for a design team by enabling thinner, higher aspect ratio wings to be weight competitive with geometrically stiffer planforms. AAW technology is currently being matured through a full-scale flight research program.[1] While this full-scale demonstration and characterization of AAW is absolutely necessary to validate the technology, transition to future air vehicles will ultimately depend on educating aircraft designers on the AAW design approach. The objective of this paper is to present findings of a lightweight fighter design study to aid future conceptual design teams in the application of AAW technology.

Impact of AAW on Conceptual Design Decisions

Conceptual aircraft design results in the specification of the vehicle geometry that will best meet the mission and design requirements. Conceptual designers quantify a number of conceptual design parameters such as wing area, aspect ratio, thickness-to-chord ratio (t/c), taper ratio, sweep angle, etc. The AAW design approach enables designers to consider configurations outside the conventional design space. Because the AAW approach enables designers to use static aeroelastic deformation as a net advantage, thinner and/or higher aspect ratio wings can be effectively employed. Previous AAW design feasibility studies have demonstrated the benefits of AAW by expanding this design space.[2,3,4,12] In addition, these studies indicate that AAW may enable configurations with dramatically reduced horizontal tail area. Based on current design methods, conceptual designers would find it difficult to choose the best configuration for an AAW design, because AAW represents a dramatic change in the design paradigm. Designers trying to employ AAW would likely have many questions and few answers. How high of an aspect ratio is feasible? How low of a wing t/c is feasible? Where should the leading and trailing edge spars be located? How should the control surfaces be sized and located? In order to effectively exploit AAW technology, designers will need benchmark design studies to reference and a design process that enables the quantification of flexibility effects on aerodynamics, control performance, loads, and structural weight.

Limitations in the Conventional Design Process

Conceptual designers typically use a combination of empirical and relatively low fidelity analytical methods, and simplify the design problem by making assumptions such as a rigid structure for the purposes of estimating aerodynamic and control performance. Designers will, in large part, quantify design parameters based on experience and a historical database of existing aircraft. The methods are generally an effective approach early in design, but their effectiveness can be limited when designing for many new technologies, such as AAW. These empirical methods were developed from a database that does not include AAW designs, and AAW represents a revolutionary shift in the design paradigm. Likewise, the analytical methods typically employed during conceptual design are not likely to be multidisciplinary and, therefore, do not account for interactions such as flexibility effects on aerodynamics, control performance, loads, and structural weight. The current approach to a conceptual aircraft design would be to constrain the design space early in the design to avoid "problems", like static aeroelastic effects, as the design progresses. These constraints would be based on the designers' experience.

In designing with the AAW philosophy, quantifying the effects of airframe flexibility is an absolute necessity. In order to account for flexibility, it is necessary to employ methods such as TSO [5] or higher fidelity finite element based methods such as ASTROS[13] or NASTRAN[14]. The problem with using such methods to influence conceptual design decisions is the time required to build the models and perform the analyses and/or design optimizations. Typically a conceptual design will undergo many changes very rapidly, and it is difficult to build the models and perform the higher fidelity analyses quickly enough to influence the conceptual design decisions. A design environment that includes parameterization of design and analysis models and associativity between the models and conceptual design parameters would enable higher fidelity models to be updated as the conceptual design parameters are changed. With this capability, higher fidelity methods could be employed to make better decisions during conceptual design.

Process and Methods Used in this Study

A lightweight-fighter mission was chosen for this design study because of the familiarity of designers with the conventional design space for this type of aircraft, and the availability of design and analysis models. Choosing this design space will provide an excellent point of comparison for designers to reference. A design process was established with methods and models available to the Air Vehicles Directorate of AFRL. Figure 2 shows the design process used in this study.

Algorithms were developed to generate wing geometry based on wing area, aspect ratio, t/c, taper ratio, and the sweep angle of a user-specified constant chord line. The algorithms also allowed for the definition of torque box geometry and a spanwise control surface break location. The algorithms assume a trapezoidal wing planform, constant t/c along the span, and four control surfaces (2 leading edge and 2 trailing edge). The entire input for all of the design and analysis models was associated with these design parameters using a Microsoft EXCEL spreadsheet environment.

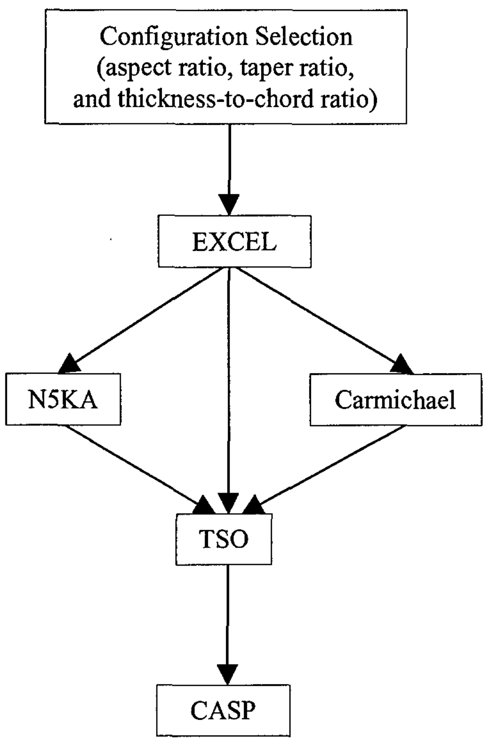

Figure 2. Design Process

For this study, the torque box and control surfaces were held constant in terms of percent chord and percent span of the wing. Also, in an attempt to isolate the effects of aspect ratio and t/c from sweep effects, the wing 40% chord was held constant at 24 degrees. This assumption was made because the 40% chord represents the maximum thickness of the airfoil, which influences structural stiffness and critical Mach number. The ¼ chord point of the mean aerodynamic chord was also held at a constant fuselage station.

TSO[5] (Wing Aeroelastic Synthesis Procedure) was chosen to conduct aeroelastic analysis and structural sizing. TSO is a multidisciplinary method that combines aerodynamic, static aeroelastic, and flutter analyses with structural optimization. It was developed by General Dynamics under an Air Force contract in the early 1970s to enable the consideration of composite structure impact on configuration selection during the early stages of the aircraft design process. TSO does not require the high degree of modeling detail that is needed by finite element methods such as ASTROS or NASTRAN, making it an ideal method for considering aeroelasticity impacts on conceptual design decisions. TSO utilizes a Rayleigh-Ritz equivalent plate technique for the wing structural model.[8,9] TSO provides the designer with a first-order estimate of structural material weight and its distribution (including composite ply orientation) required to meet strength and aeroelastic requirements. TSO's simplicity does bring with it additional limitations. TSO sizes

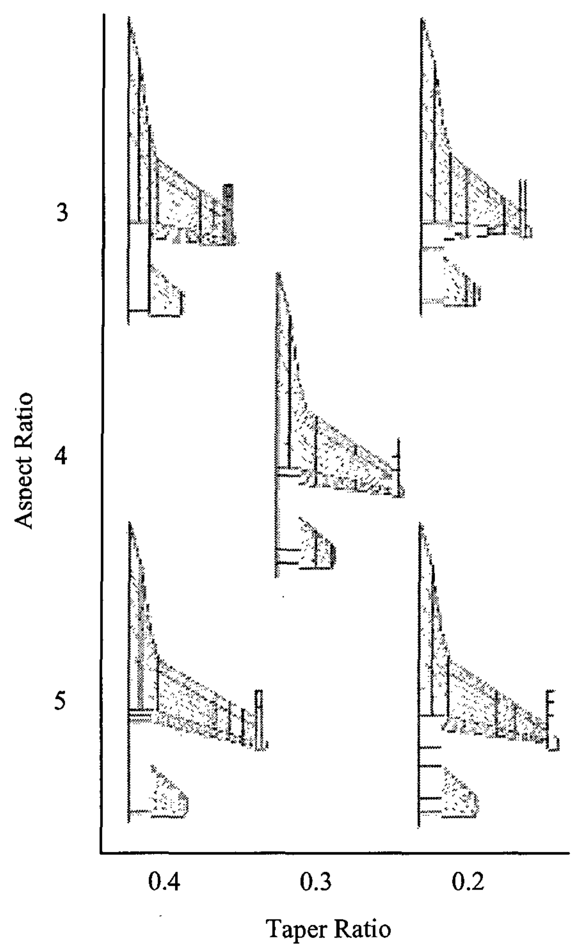

Figure 3. Range of Configurations Investigated

only the wing skins, and the upper and lower wing skins are constrained to be the same thickness. The wing substructure weight is calculated using a density factor and internal wing box volume. There are no buckling constraints. The load conditions are limited to two symmetric conditions and one asymmetric condition. A 9 g symmetric pull-up at Mach 0.9 and 10000 ft, a 7.2 g symmetric pull-up at Mach 1.2 and 10000 ft, and a 7.2 g, 100 degree/sec rolling pull-out at Mach 1.2 and 10000 ft were used in this study. The Carmichael linear aerodynamic method[15] was used for steady aerodynamic loads, and the N5KA doublet lattice method[5] was used for unsteady aerodynamics. The steady aerodynamic model, shown in Figure 4, used 398 panels for the semispan configuration. The unsteady aerodynamic model was a wing only model, extending to the side of body. The flutter analyses were based on Mach 0.9, sea level conditions. The optimization approach in TSO is a Davidon-Fletcher-Powell unconstrained minimization with a penalty function to account for constraints.

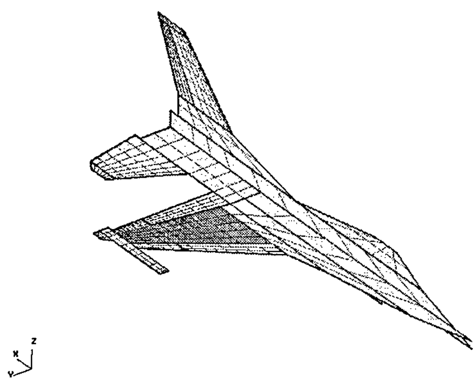

Figure 4. Steady Aerodynamic Model (wing control surfaces and structural box highlighted)

For each configuration, N5KA and Carmichael [5] were executed to provide the aerodynamic data needed for TSO. A TSO structural optimization was completed for both the conventional philosophy and the AAW philosophy. The wing box skin thickness was represented by a quadratic polynomial in both the chordwise and spanwise directions. The coefficients of this polynomial and the orientation of the composite laminate were chosen as the structural design variables. The TSO model also accounted for the flexibility of the control surfaces; however, the fuselage and empennage were considered to be rigid. Both the conventional and the AAW models utilized strength constraints on the wing using strain allowables (.003 in/in tension and compression and .01 in/in shear at limit load) consistent with damage tolerance requirements. Additional constraints included a minimum allowable flutter speed of 780 knots at sea level, a minimum gage of .005" per ply (0, +/-45, 90 laminate), and a maximum thickness per ply of 70% total skin thickness. The structural constraints were evaluated at 24 points distributed over the wing box. The experience of the authors is that the TSO design will typically be somewhat lighter than a finite element model prediction due, in part, to the limited number of evaluation points; however, the trends over the design space should be consistent with the finite element designs.

In design optimization using the conventional philosophy, aircraft trim was satisfied using angle-of-attack and horizontal tail deflection for the symmetric maneuvers. For the antisymmetric portion of the asymmetric maneuver, the aileron and horizontal tail were used to generate rolling moment with a horizontal tail-to-aileron blend ratio of 0.33. In addition to the constraints mentioned above, the conventional cases were also designed to meet a roll effectiveness constraint. This constraint was defined such that the minimum roll moment flexible-to-rigid ratio of the aileron was 0.62 at the Mach 0.9, 10,000 ft. condition. This value was chosen based on the authors' experience to maintain some contribution from the wing to maneuvering forces. For the supersonic asymmetric design condition, the horizontal tail could provide sufficient rolling moment; however, this would induce large weight penalties in the aft fuselage and empennage, and large yaw moments during the roll maneuver. These are both undesirable from a vehicle design standpoint, and could not be accounted for in the models used for this study.

The AAW design philosophy incorporated a gearing of the four wing control surfaces along with the angle-of-attack and horizontal tail deflection to trim for each symmetric condition. An antisymmetric component gearing of the four wing control surfaces was added to the symmetric gearing ratio for the asymmetric condition. The horizontal tail was not deflected to generate rolling moment. The gearing ratios were determined through a separate trim optimization model described in References 10 and 11. The authors also tried other gearing ratios, based on their experience, for the antisymmetric portion. Both the symmetric and antisymmetric gearing ratios allowed maneuver load control to be employed. The maximum deflections allowed for symmetric maneuvers were $\pm$30 deg. on the wing trailing edge surfaces, and +30/0 deg. on the leading edge surfaces (all surface deflections are positive down). The antisymmetric deflections were limited to $\pm$5 deg. for all wing control surfaces in the AAW models.

Based on the optimized structural designs for the AAW and conventional approaches, a ratio of the TSO wing weight predictions for each approach was then determined. This ratio was then used as a technology factor to be applied to the wing box structural weight equation in a vehicle synthesis procedure to represent the wing structural weight advantage of the AAW design philosophy. This technology factor was assumed to be constant for a configuration over a range of vehicle design weights.

CASP (Combat Aircraft Synthesis Program)[6] was the method chosen to conduct vehicle sizing. It is typical of many vehicle synthesis procedures in that it utilizes statistically based methods for weight estimation. The aerodynamics and control analyses are based on Digital Datcom[7] empirical methodology. CASP has several sizing options available, but the program was only executed in a single point design mode and was used to minimize take-off gross weight (TOGW) for a typical lightweight fighter air-to-air mission. Vehicle sizing is driven by range requirements, and point performance metrics do not drive sizing in CASP. To ensure comparable maneuverability levels between configurations, wing loading (83 psf), vehicle thrust-to-weight ratio (0.8), and static margin (0.01) were held constant for all configurations for both the conventional and AAW design approaches.

Design Study Results

Table 1 shows the configurations that were investigated. This matrix was chosen to facilitate a Design of Experiments and statistical multivariate regression analysis as described in Reference 10. Least squares fits of a second order polynomial were used to generate approximate models of the design space with respect to wing box skin weight and TOGW. These approximate models were then used to provide the graphical representation of the design space in Figures 5 through 8. Table 1 also shows the technology factor used to account for AAW structural wing box weight savings for each configuration. The aspect ratio 5, t/c 0.03 configurations did not meet all of the design requirements for the conventional design philosophy. The taper ratio 0.2 configuration could only achieve a roll effectiveness value of 0.56, while the taper ratio 0.4 configuration could only achieve a roll effectiveness value of 0.34 and a roll rate of 50 deg/sec. The other conventionally designed configurations met all of the design requirements. All of the configurations using the AAW approach met the design requirements. Despite the inability of two of the conventionally designed configurations to meet the requirements, the authors chose to use these values in order to enable the regression analysis and graphical representation of the design space. However, it is likely that the technology factor for these two configurations would be lower than the values used. Table 1 also shows that the roll effectiveness constraint was active for each configuration using the conventional design approach.

aspect ratio	t/c	taper ratio	tech factor	conv active constraints	AAW active Constraints	conv TOGW	AAW TOGW
3	0.030	0.2	0.87	1,5	2,3,4	1.053	1.021
3	0.060	0.2	0.84	1,2,3	2,3	1.084	1.040
3	0.030	0.4	0.91	1,2,3	2,3,4	1.195	1.149
3	0.060	0.4	0.82	1,2,3	2	1.395	1.294
5	0.030	0.2	0.46*	1,2,3	2,3,4	1.219	0.871
5	0.060	0.2	0.66	1,2,5	2,3,5	1.159	1.009
5	0.030	0.4	0.62*	1,2,3	2,3,4	1.832	1.247
5	0.060	0.4	0.48	1,5	2,3,4	1.688	1.374
3	0.045	0.3	0.74	1,2,5	4	1.115	1.045
5	0.045	0.3	0.53	1	2,3,4	1.336	1.041
4	0.045	0.2	0.63	1,3	3,4	1.052	0.935
4	0.045	0.4	0.63	1,5	2,3,4	1.408	1.219
4	0.030	0.3	0.52	1,2,3	2,3,4	1.261	0.984
4	0.060	0.3	0.73	1,2	2,3,5	1.283	1.176
4	0.045	0.3	0.57	1,2,3,5	3,4	1.210	1.029

Constraint Key
1- Roll effectiveness
2- Minimum gage
3- Strength
4- Flutter
5- Ply thickness %

* Conventional design did not meet all design requirements

Table 1. TSO Design Results Summary

Other than for the highest t/c configurations, flutter became an active constraint for the AAW designs. The final two columns of the table show the results from the vehicle synthesis for each configuration. The TOGW values for the conventional and AAW designs are normalized by the lowest conventional design TOGW. Based on the approximate model derived from the regression analysis, the lowest TOGW for the conventional approach was found to be an aspect ratio 3, taper ratio 0.2, and t/c 0.04 configuration. The table shows that the best configuration for the AAW design approach was an aspect ratio 5, taper ratio 0.2, and t/c 0.03 configuration. The data indicates that the TOGW savings due to AAW is approximately 13% for this lightweight fighter mission. The reader should note that the technology factor used for this configuration was likely not as low as it would have been had the conventional design met all of the design requirements.

Conventional design wisdom indicates that wing box structural weight increases directly with aspect ratio and taper ratio, and inversely with t/c over the range of the variables in this study. Figure 5 clearly shows these trends. In these figures, the wing box structural weight has been normalized to that of the lowest conventional TOGW configuration (aspect ratio 3, taper ratio 0.2, and t/c 0.04). Figure 6 presents the wing skin weight vs. aspect ratio for a t/c of 0.03 and 0.045. The figures also show that the sensitivity of wing box structural weight with respect to aspect ratio and t/c is less for an AAW approach than a conventional approach especially as aspect ratio increases and t/c decreases beyond the conventional design space. AAW philosophy should enable an expansion of the design space for a lightweight fighter design. Figure 7 shows the impact of the

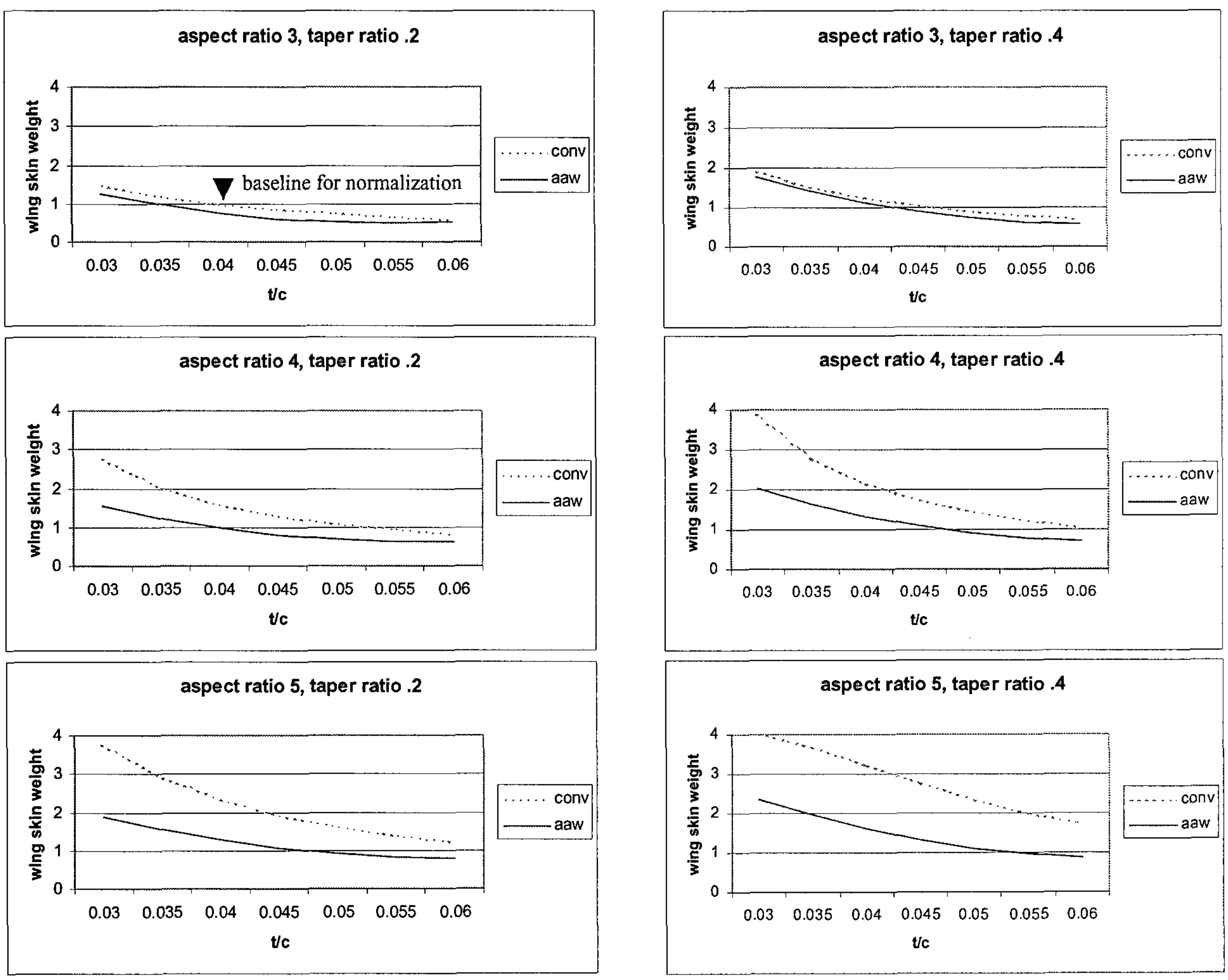

Figure 5. Summary of wing box skin weight vs t/c

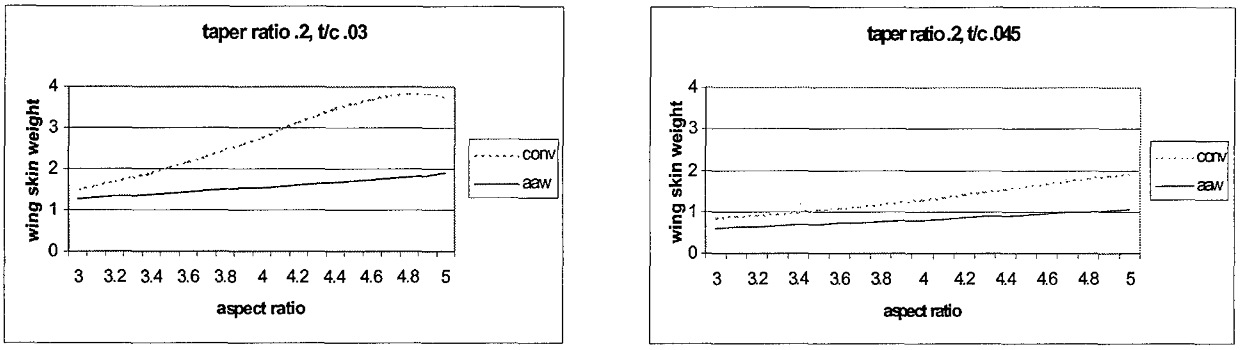

Figure 6. Summary of wing box skin weight vs aspect ratio

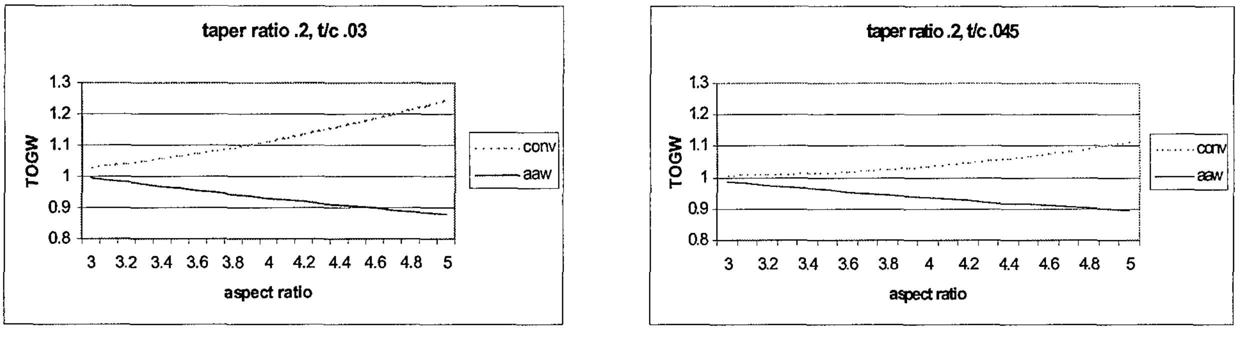

Figure 7. Summary of TOGW vs aspect ratio for taper ratio 0.2

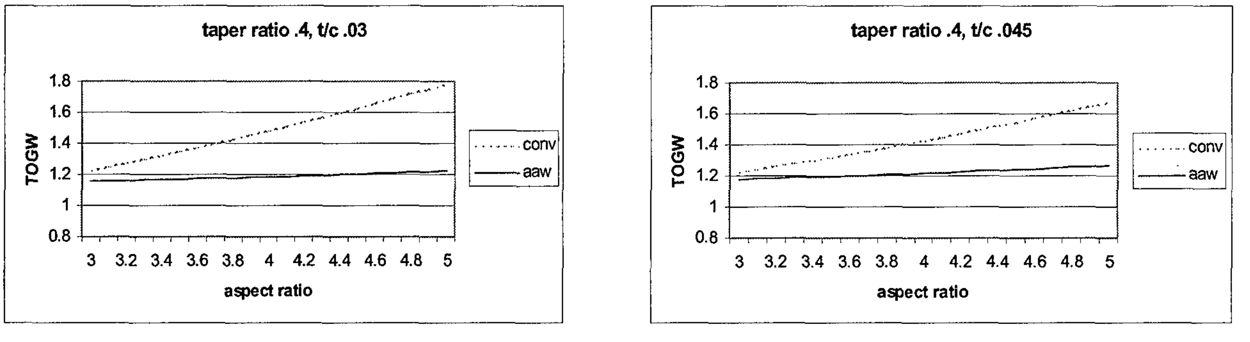

Figure 8. Summary of TOGW vs aspect ratio for taper ratio 0.4

AAW approach on TOGW for the same range of variables shown in Figure 6. Figure 8 shows the impact on TOGW for taper ratio 0.4. It is interesting that the sensitivity of TOGW with respect to aspect ratio is highly dependent on taper ratio, and results in a change of sign in the AAW design space. The reader should notice a slight downward turn of the curves representing the conventional approach at the highest aspect ratios. This is due to the inclusion in the approximate models of the two conventional cases mentioned above that did not meet all of the design requirements.

Conclusions

This study demonstrated that AAW technology can have a significant effect on conceptual aircraft design decisions, and enable expansion of the feasible design space for a lightweight fighter aircraft. In order to implement the AAW design approach, design teams must account for structural flexibility throughout the design process. This study demonstrated the importance of accounting for structural flexibility at the earliest stage of the design process, if a configuration is to be selected that takes maximum advantage of the technology.

The parameterization of the design and analysis models used in this study facilitated its completion in a timely manner. This study utilized approximate methods typically not used in the conceptual design phase. The TSO method provided timely results, however, its approximations necessitate user expertise to acquire meaningful information. Higher fidelity design and analysis methods and more complete aircraft models are required to refine the data and better quantify savings. The authors realize that extrapolation of the empirical structural box weight equation in the vehicle synthesis tool may result in inaccuracies. While this study demonstrates that benefits due to the AAW design approach exist, the extent of the benefits may be difficult to completely assess with these methods. The reader should note several issues that could affect the results of this study; 1) the AAW designs may incur a relatively small weight penalty for leading edge surface actuation hardware, 2) it is likely that better gearing ratios for the AAW designs could be found with an improved design method, 3) the AAW designs would likely benefit from other configuration changes such as a reduction in horizontal tail area, and 4) additional load conditions and design requirements could affect structural sizing.

Related/Future Work

Reference 10 documents a similar study using an ASTROS finite element design model. The authors compared the designs from both studies and found similar trends in the predicted weight benefits.

The authors recognize many opportunities for extending this effort. It would be interesting to investigate the effect of other design parameters such as wing box geometry, control surface sizing, maneuver requirements, wing area, and vehicle design weight on the benefits of the AAW approach. Improvement in the optimization methodology to enable more optimal gearing ratios, simultaneous structure and controls optimization, and possible configuration optimization will be considered for further investigation. Additional AAW design guidance will be developed through the correlation of full scale flight test data with higher fidelity analytical predictions and scaled experimental predictions.

Acknowledgement

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